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# A retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs

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## Abstract

We perform a retrospective investigation of multi-decade trends in price and life-cycle cost (LCC) for home appliances in periods with and without energy efficiency (EE) standards and labeling policies. In contrast to the classical picture of the impact of efficiency standards, the introduction and updating of appliance standards is not associated with a long-term increase in purchase price; rather, quality-adjusted prices undergo a continued or accelerated long-term decline. In addition, long term trends in appliance LCCs—which include operating costs—consistently show an accelerated long term decline with EE policies. We also show that the incremental price of efficiency improvements has declined faster than the baseline product price for selected products. These observations are inconsistent with a view of EE standards that supposes a perfectly competitive market with static supply costs. These results suggest that EE policies may be associated with other forces at play, such as innovation and learning-by-doing in appliance production and design, that can affect long term trends in quality-adjusted prices and LCCs.

 Online supplementary data available from [stacks.iop.org/ERL/9/114010/mmedia](http://stacks.iop.org/ERL/9/114010/mmedia)

Keywords: energy efficiency, learning, policy analysis

## 1. Introduction

Energy efficiency (EE) standards are widely viewed as a key policy tool for reducing energy consumption, saving money, and mitigating climate change [1]. There has been substantial debate, however, in both the academic literature and the political discourse regarding the impact of standards on both the purchase price and life-cycle cost (LCC) of ownership of

home appliances. Many studies argue that appliance standards achieve a net neutral or beneficial economic impact by decreasing the present value of operating energy costs more than the expected increase in purchase price [2–6]. Other papers assert that such mandates as EE standards are an inefficient and costly means of decreasing CO<sub>2</sub> emissions based on assumed parameters [7] or are likely to lead to expensive products that may force budget-constrained consumers to choose products of lower quality or reduced features [8]. Despite the number of studies, there has been little research into the impact that EE standards may have had on long-term price or LCC trends. This paper examines these trends and suggests that the EE standards reviewed here are



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correlated with an accelerated decline in LCC, and are sometimes correlated with an accelerated decline in prices. Given the correlations documented in this study, further research into the dynamics of appliance prices and LCCs would be valuable.

When EE impacts are examined in a short-term analytical framework, the primary problems addressed by the regulation are market failures associated with environmental externalities, imperfect information, principal-agent issues, liquidity constraints, or behavioral anomalies [9]. Energy policies, such as minimum EE standards and labeling policies (e.g., ENERGY STAR Program), are devised to address these market failures and informational problems that lead to socially suboptimal outcomes. In the classical regulatory impact analysis picture, labels and mandates bring the market to a new equilibrium where appliances have higher prices and lower operating costs. The lower operating costs and internalized market externalities of the more efficient appliances are thought to justify the higher purchase prices paid by consumers.

This paper contributes to the literature made up by recent empirical market studies indicating that appliance price–efficiency relationships may be far from static [10]. Some studies argue that prices decline faster than forecast in regulatory analyses due to technological innovation [11]. Additionally, a recent study of the 2004 and 2007 US EE standards for clothes washers observed that the rate of decline in appliance prices appeared to accelerate after the EE standards came into effect [12]. This observation is largely inconsistent with the static picture of price–efficiency relationships, which would have predicted a price increase. As a growing number of observers examine the retrospective data on appliance price changes associated with EE standards, there appears to be an expanding body of evidence suggesting that the traditional static picture of EE standards impacts on costs may be inconsistent with observed market behavior [13].

In particular, though only a few studies specifically examine the case of EE policies, there exists a fairly extensive literature on ‘induced innovation’ [14]. This literature discusses a diverse range of cases where regulation may have induced innovations by private firms [15]. When regulation induces innovation, the well-known market failure regarding underinvestment in research, development and innovation [14, 16, 17] may be addressed. The structure of the supply markets for appliances may lead to underinvestment in innovation, thus hindering EE in the menu of products offered to consumers [18]. There is also evidence that the supply markets for appliances are characterized by varying levels of industry concentration, which can lead to price discrimination and under-investment in EE by manufacturers [12, 19–21].

In this paper, we investigate long-term trends in appliance prices and LCCs in an effort to better understand potential interactions between policy and rates of change in appliance markets. Specifically, we estimate long-term rates of change of appliance prices and LCCs for multi-decade periods before and after the initiation of active EE standards for several appliances. Our analysis considers mandatory EE standards, but EE labeling programs, which were

implemented in conjunction with standards in the US, may also contribute to the ability of consumers to make cost-effective trade-offs between the price of efficiency and energy-cost savings [22].

First, we examine experience curves (also called learning curves) for appliance prices and LCCs for five cases: refrigerators, clothes washers, room air conditioners, and clothes washers in the US, and refrigerators in the Netherlands. We calculate for each curve the time and magnitude of the most significant downward inflection point during the multi-decade period of observation and calculate the extent to which that inflection point is correlated with the start date of EE policies.

Next, we examine data on price–efficiency curves over more than a decade, and we assess the approximate rate of change in the incremental price of efficiency implied by long term changes in the price–efficiency curves. We observe that the implied rate of change in the incremental cost of efficiency is much faster than the long term rate of change in the appliance base price.

Finally, we provide a set of mathematical equations for time-varying price–efficiency relationships and discuss how such equations could potentially be useful in designing dynamic policies to minimize appliance LCCs for consumers in the face of dynamic changes in appliance price and the price–efficiency relationship.

## 2. Defining price and LCC

EE standards effectively mandate the manufacturing of appliances and equipment that may have a higher price but which have lower operating costs. Throughout this paper, the term ‘price’ refers to the quality-adjusted<sup>3</sup> purchase price of an appliance, unless otherwise indicated. The total consumer impacts of EE standards are estimated by calculating the energy-related<sup>4</sup> LCC of an appliance, which is a sum of the price  $P_A$  and the energy-related operating costs over time,  $OC(t)$ . LCC includes a discounted sum of operating costs, because money spent on operating costs  $y$  years in the future is worth less than the same amount of money in the present which could be invested at some interest rate<sup>5</sup>. Assuming a yearly compound interest rate  $i$ , the total present value of operating costs over the appliance lifetime of  $L$  years is given by

$$PVOC_L = \sum_{y=1}^L \frac{OC(y)}{(1+i)^y}. \quad (1)$$

<sup>3</sup> Because the attributes of appliances change over time, quality-adjustments allow for the comparison of prices of appliances in different decades.

<sup>4</sup> This analysis assumes that non-energy related operating costs (e.g., maintenance and repair costs) are independent of EE and therefore irrelevant to the effect of EE policy on LCC.

<sup>5</sup> If operating cost is measured in inflation-adjusted dollars, the inflation-adjusted interest rate is used. We assume operating costs and interest are charged at the end of the year in which they occur.

The sum of price and present value of operating costs then provides an estimate of the LCC of that appliance:

$$\text{LCC} = P_A + \text{PVOC}_L. \quad (2)$$

### 3. Modeling price and LCC trends as experience curves

Experience curves can be used to describe price trends for many technologies<sup>6</sup> by modeling price  $P$  as a power-law function of the total cumulative quantity  $Q$  of units deployed:  $P = P_o Q^{-b}$  where  $P_o$  and  $b$  are empirically determined parameters [23–25].  $Q$  is the observable variable used as proxy for cumulative manufacturing experience [26]. The parameter  $b$  is a parameter that describes the relation between fractional increases in experience and fractional declines in price. The experience curve concept is based on the empirical observation that people and organizations complete tasks more efficiently as they accumulate experience, thus reducing the marginal cost of production. However, there are other mechanisms that could also yield a correlation between price and cumulative experience (e.g., changes in pricing strategies or globalization of manufacturing operations and supply chains). In this study, we will use the phrase *experience curve* as shorthand to refer to any empirical correlation between price and cumulative experience, without necessarily linking observed trends to learning-by-doing processes.

To calculate each experience curve, we estimated inflation- and quality-adjusted prices over time by projecting a reference price and quality from 2008 into the past using a product-specific price index. Price indices provide a method of accounting for changes in the mix of products offered in the market, as well as the quality and features of those products. For example, the refrigerators that were available for sale in the 1960s are no longer available today, and the technologies, features and configurations of refrigerators today did not exist in the 1960s. Any measurement of long term price trends needs to account for these gradual but significant changes if the researcher wishes to interpret the results as quality-adjusted.

For US data, we use price indices published by the Bureau of Labor Statistics (BLS) and the Bureau of Economic Analysis. (See the supplemental information (SI) for additional detail regarding price indices and the calculation of experience curves.) The BLS provides both consumer price indices for retail purchase prices and producer price indices for the prices received by producers for their products. We use the all-items consumer price index (CPI) to adjust for inflation in our analysis. In some cases our CPI data is sourced indirectly from the BLS using tables published by Gordon [27].

In the LCC calculations, to estimate an average price in a recent year, we use the shipment-weighted average price

obtained from the LCC spreadsheets associated with the Department of Energy's (DOE) most recent rulemaking or notice of proposed rulemaking for a particular appliance. These spreadsheets are available on the DOE's Appliance Standards website as part of technical support documents created for each rulemaking. We obtain the historical inflation- and quality-adjusted prices by multiplying this recent shipment-weighted price by the appropriate inflation- and quality-adjusted price index.

We obtained data to estimate historical average energy use from a variety of different sources, including the Association of Home Appliance Manufacturers recent DOE rulemakings, DOE's Energy Information Administration's (EIA) Residential Energy Consumption Surveys [28], and the published literature [29]. For periods with missing or incomplete data, we interpolate from the historical trends. In the case of clothes washers, we also consider water usage and water efficiency when calculating operating costs. Water usage data were obtained from recent DOE rulemakings.

We use historical average annual retail prices of electricity for residential consumers from the Annual Energy Review published by EIA [30]. For years prior to 1960, we extrapolate the retail price of electricity using the CPI for electricity [31]. In the case of water, the average retail price in 2008 was obtained from a 2008 water and wastewater rate survey [32], and extrapolated to prior years using the CPI for water and sewage maintenance.

Cumulative unit shipments to the US market for each product are estimated using annual shipment data from recent DOE rulemaking analyses. Other inputs to the LCC calculation, such as the appliance lifetime and discount rate, are similarly estimated using data from these DOE analyses. We follow DOE's practice of using a weighted-average consumer cost of capital from a variety of debt and asset classes to represent the discount rate, because that average represents the financial cost of money to a consumer. For a review and discussion of the issues surrounding discount rates and the EE gap, we recommend Jaffe and Stavins [33]. Depending on the rulemaking, the average discount rate for each appliance type was found to be  $5.0 \pm 0.5\%$ . For simplicity, we use an average real discount rate of 5.0% in the LCC calculations for all appliances.

For refrigerators in the Netherlands, we obtained price and energy use data from Weiss *et al* [34] and from the German market research firm The GfK Group. These refrigerator price data are not quality-adjusted. We calculate the inflation adjustment using the Harmonized Index of Consumer Prices from Eurostat [35]. We obtained nominal pre-tax electricity prices from Eurostat [36], and estimate post-tax electricity prices using tax rates from the U.K. DOE and Climate Change [37]. We use the average tax rate for 2008 and 2009 as the assumed tax rate for the analysis period. Historic shipments were obtained from an Ecocold report [38]. Shipments to the EU-15 nations were used as the basis for experience, since manufacturers tend to sell products across the European market. The lifetime and discount rates are assumed to be constant in time and the same as those of US refrigerators.

<sup>6</sup> The experience curve literature focuses on product cost rather than price. Although price often deviates from the cost of production, we assume that on average the price trend is a good approximation of the cost trend.

The ultimate product of this data collection, processing, and integration is a set of yearly time series for cumulative shipments, prices, and LCCs, for four US appliances and for refrigerators in the Netherlands. Shipments data refer only to the US market (or the EU market for Netherlands refrigerators). Global shipments would be a closer indicator of cumulative experience, but provided that manufacturers' global shipments grow consistently with their US/EU shipments, power-law experience curves can be accurately fitted using the more limited data set. We combine the price and LCC data with the shipments data to obtain experience curves,  $P(Q)$  and  $LCC(Q)$ .

#### 4. Efficiency policy and changes in long term trends

Figure 1 shows the results of fitting experience curves to price and LCC for four major US appliances (refrigerators, clothes washers, room air conditioners and central air conditioners) and for refrigerators in the Netherlands. These products were chosen because multi-decadal information was available both during a period in which there are no requirements for minimum EE performance ('pre-standards'), and during a period in which there are a series of periodically updated minimum EE performance requirements ('post-standards'). In all cases, the price and LCC generally decline with time, and a significant transition can be seen in the LCC decline rate parameter near the initiation of standards. A distinct acceleration of the price decline can also be seen for clothes washers, room air conditioners, central air conditioners, and refrigerators in the Netherlands. This break in trend is unexpected from a classical economics perspective, and more research is necessary to understand the cause of the observed behavior.

We consider the post-standards period to begin after the compliance date of the first standard likely to affect the market under consideration. In most cases, the first standard corresponds to a federal standard, or to a European Union standard in the case of refrigerators in the Netherlands. We also consider California standards given that California is the most populous US State and therefore constitutes a significant fraction of the US appliance market. In some cases, California efficiency standards may have been effectively treated as a national standard by manufacturers. In general, no lag time is observed between the compliance date and the acceleration of price and LCC declines; this may stem from the fact that new standards are typically announced several years before the compliance date, giving the market time to respond. This study uses the compliance date as the start date of the policy because this is the date on which the policy officially takes effect. The market may begin to respond with more efficient products earlier than the compliance date if market actors are confident that standards are likely to occur. Distinct accelerations of the price and LCC decline are not always seen for subsequent standards, perhaps because during the post-standards period manufacturers are aware of potential updates to EE standards and more EE information may be available to consumers via labels. This study focuses on how cost trends

may differ between periods with and without active EE standards policies.

We fit the data with a simple mathematical model that includes two power-law experience curves with different decline-rate parameters  $b$ , corresponding to the periods before and after a transition year. The decline rates, transition year, and overall normalization are treated as free parameters, allowing us to calculate the transition year within a 95% confidence interval using standard maximum-likelihood techniques. (See the SI for further details. The SI also evaluates the sensitivity of results to variations in model formulation). Table 1 provides the resulting transition years and confidence intervals of these experience-curve fits for US refrigerators, clothes washers, room air conditioners, central air conditioners, and Netherlands refrigerators, and compares them to the first year of efficiency standards for these products.

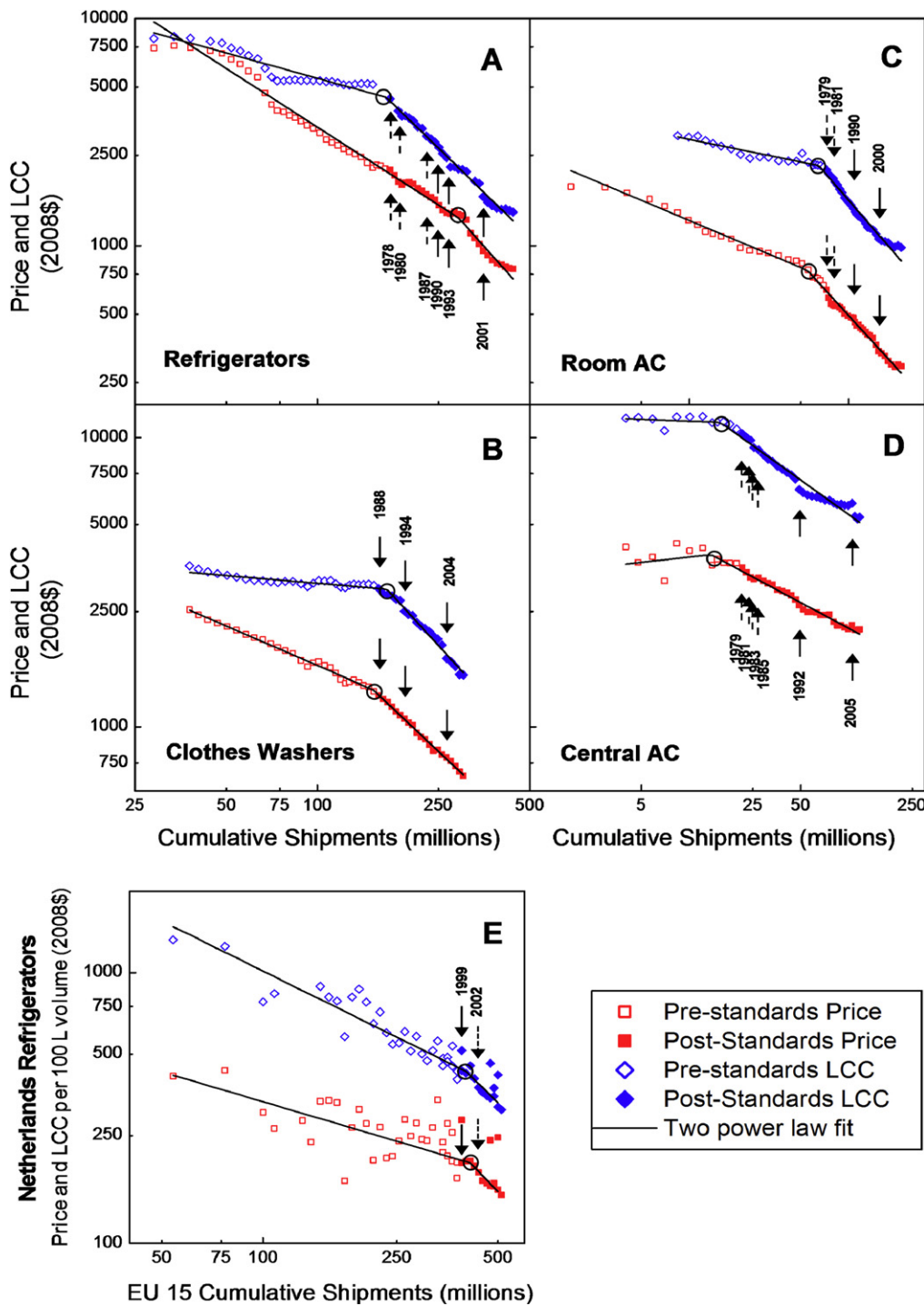
The correspondence between calculated transition year and first efficiency standard year can be seen in figure 2 with 95% confidence intervals shown as error bars. In almost all cases, the data yield a transition year that is close to the onset of standards, with the exception of US refrigerator price. The confidence intervals for the Netherlands refrigerator case are relatively large because of the larger variance in the available price and efficiency data.

Previous studies have identified changes in energy prices as a potential driver for improvements in EE [14]. Increasing electricity prices during the 1970's were a primary driver for the promulgation of the first US EE standards in the Energy Policy and Conservation Act of 1975. However, in spite of a consistent inflation-adjusted electricity price decline from 1983 to 2002, the accelerated rate of decline in appliance costs persisted. This is not consistent with electricity prices being the primary driver for the accelerated rate of decline in appliance costs.

#### 5. Trends in the incremental price of efficiency: the case of US refrigerators

The price and LCC trends observed in figure 1 clearly diverge from historical, pre-2011 US regulatory forecasts included in technical support documents for energy conservation standards for refrigerators [39–43], which assumed no future price declines in the absence of new standards, and which projected an increase in price following the introduction and subsequent updates of standards. We compiled historical, engineering-based estimates of the relationship between price and efficiency that were developed in DOE regulatory analyses accompanying the consideration of new or updated efficiency standards for refrigerators. For refrigerators, new mandatory Federal EE standards had initial compliance dates of 1990, 1993, 2001 and 2014, with supporting analyses performed in 1982, 1987, 1989, 1995, and 2010. At the time each analysis was done, the incremental cost of higher efficiency was based on the current market costs of introducing technologies to achieve a given efficiency. The full historical sequence of price–efficiency engineering estimates for 17- to 18-cubic-foot refrigerators with





**Figure 1.** Price and LCC trends for appliances pre-standards and post-standards. Unfilled symbols indicate pre-standards data, while solid symbols indicate the post-standards era. Lines indicate best-fit experience curves from the two-trend model. Circles indicate transition points in the decline rates. Data are shown for United States (A) refrigerators, (B) clothes washers, (C) room air conditioners, and (D) central air conditioners, as well as for (E) Netherlands refrigerators. Netherlands refrigerator price and LCC are shown per 100 liters of volume, and cumulative shipments are for the EU. In figures 1(A)–(D), the dashed and solid arrows represent California and Federal standards, respectively. In figure 1(E), the dashed arrows indicate a voluntary agreement with manufacturers, and solid arrows indicate mandatory standards.

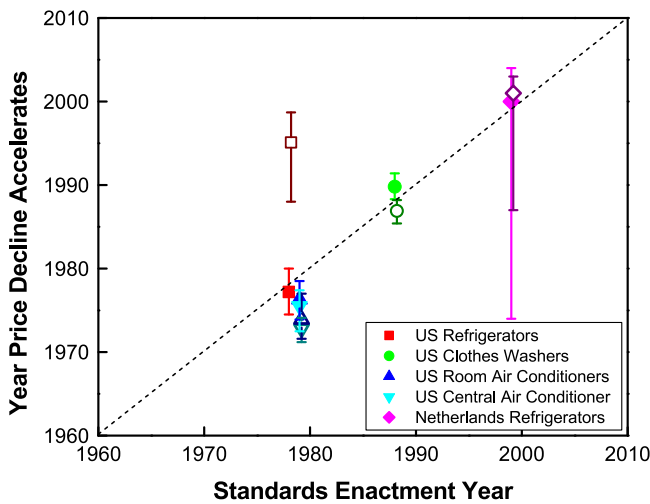
top-mount freezers and automatic defrost is shown in figure 3(A). Note that the most energy-efficient refrigerator considered in 1989 had higher energy use than the least efficient refrigerator considered in 2010, and the estimated price of achieving that efficiency was roughly twice the price estimate of the least efficient 2010 refrigerator. Over the period considered,

the efficiency of the least efficient refrigerator on the market improved at an average rate of 4% per year while its price dropped 2.5% per year.

We mathematically characterize the price–efficiency relation as a baseline price  $P_{\min}$  plus a power-law relation between unit energy consumption (UEC) and the additional

**Table 1.** Results for least-squares, two-slope experience curve model fit of price and LCC for the appliances considered in this study; 95% confidence intervals were calculated from the appropriate  $\chi^2$  distribution. For reference, the year of the first efficiency standard implementation is also shown for each appliance.

Appliance	First efficiency standard year	Transition year		Pre-transition decline rate <i>b</i>		Post-transition decline rate <i>b</i>	
		LCC	Price	LCC	Price	LCC	Price
Refrigerators (US)	1977	1977.2 <sup>+2.3</sup> <sub>-3.2</sub>	1995.0 <sup>+3.7</sup> <sub>-8.0</sub>	0.36 <sup>+0.01</sup> <sub>-0.08</sub>	0.84 <sup>+0.05</sup> <sub>-0.00</sub>	1.25 <sup>+0.00</sup> <sub>-0.05</sub>	1.51 <sup>+0.04</sup> <sub>-0.14</sub>
Clothes washers (US)	1988	1989.8 <sup>+1.9</sup> <sub>-1.2</sub>	1986.9 <sup>+1.3</sup> <sub>-1.5</sub>	0.12 <sup>+0.04</sup> <sub>-0.00</sub>	0.45 <sup>+0.03</sup> <sub>-0.03</sub>	1.20 <sup>+0.01</sup> <sub>-0.10</sub>	0.98 <sup>+0.00</sup> <sub>-0.03</sub>
Room air conditioners (US)	1979	1976.3 <sup>+1.8</sup> <sub>-2.8</sub>	1972.8 <sup>+1.3</sup> <sub>-1.6</sub>	0.16 <sup>+0.04</sup> <sub>-0.01</sub>	0.27 <sup>+0.01</sup> <sub>-0.04</sub>	0.76 <sup>+0.00</sup> <sub>-0.04</sub>	0.75 <sup>+0.01</sup> <sub>-0.04</sub>
Central air conditioners (US)	1979	1975.5 <sup>+4.0</sup> <sub>-0.9</sub>	1973.9 <sup>+3.1</sup> <sub>-2.3</sub>	0.01 <sup>+0.03</sup> <sub>-0.00</sub>	0.07 <sup>+0.03</sup> <sub>-0.03</sub>	0.39 <sup>+0.02</sup> <sub>-0.03</sub>	0.28 <sup>+0.00</sup> <sub>-0.03</sub>
Refrigerators (Netherlands)	1999	2000 <sup>+4</sup> <sub>-26</sub>	2001 <sup>+2</sup> <sub>-14</sub>	0.45 <sup>+0.14</sup> <sub>-0.15</sub>	0.25 <sup>+0.32</sup> <sub>-0.14</sub>	1.08 <sup>+0.11</sup> <sub>-0.11</sub>	0.80 <sup>+0.12</sup> <sub>-0.12</sub>



**Figure 2.** The calculated year of transition to an accelerated price or LCC decline, as a function of the year in which the first standard was enacted for an appliance. Open symbols correspond to price transition year, closed symbols to LCC transition year. Price transition year data points are a darker shade of color and have been offset slightly in the horizontal direction for clarity. If the change in slope of the experience curves in figure 1 occurred at the compliance date of the standard, the data points would lie on the dashed line. There appears to be a correspondence between the year an acceleration in price and LCC decline occurs and the transition year from a pre- to post-standards era. Note that while the 1970's inflection points occurred while electricity prices were increasing, the clothes washer inflection point occurred in an era with decreasing real electricity prices.

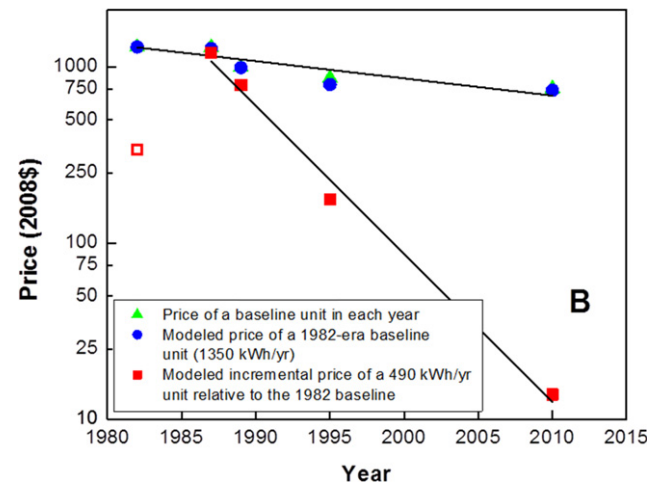
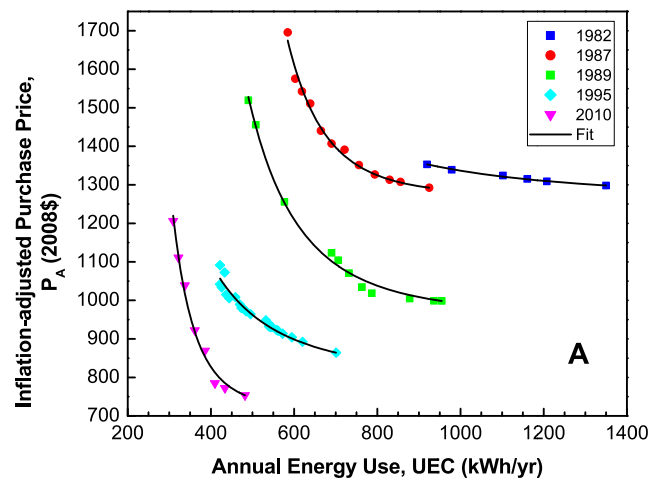
price of achieving that efficiency level:

$$P_A(\text{UEC}) = P_{\min} + R_{\text{UEC}} \left( \frac{\text{UEC}}{\text{UEC}_0} \right)^{-\epsilon} \quad (3)$$

Here,  $P_{\min}$  is the minimum price of an appliance,  $R_{\text{UEC}}$  is the additional price required to purchase an appliance whose energy consumption takes a reference value  $\text{UEC}_0$  (which we are free to choose), and  $\epsilon$  is the power-law exponent, which, in economic terms, represents the elasticity of the energy-related price component with respect to efficiency. Figure 3(A) illustrates a reasonably good fit to the engineering-based price–efficiency estimates using this simple functional form, where we have fit the model in (3) to each of the five price–efficiency estimates separately, yielding five sets of fit parameters (see table 2).

From these fits we can estimate the evolution of the price of a refrigerator with fixed efficiency and of the incremental price of a fixed increase in efficiency. For each of the five fits shown in figures 3(A) and (B) shows the engineering-based estimate of baseline price, the price of a 1982-era baseline unit modeled using equation (3), and the modeled price increase required to improve the 1982 baseline unit to a reference energy consumption of  $490 \text{ kWh yr}^{-1}$ , a value chosen since it lies in or near the range of UEC values covered by most of the engineering estimates after 1982.

The evolution of our fit parameters over time demonstrates that the price of efficiency declines at a much faster rate than the price of the baseline appliance. We can quantify this by fitting our price measurements to a Moore's-law type



**Figure 3.** Modeling of energy use versus price. (A) Engineering-based estimated price of US 17- to 18-cubic-foot top-mounted refrigerator-freezers as a function of annual energy use, from DOE technical support documents. Solid lines show the fit to the data using equation (2). (B) Evolution in the modeled price of the baseline, least efficient refrigerator on the US market in each year (green points); a refrigerator with a fixed efficiency of a 1982-era baseline unit (blue points); and the incremental price associated with a fixed efficiency increase relative to the 1982 baseline (red points). Solid lines show the exponential fit of (4) to the red and blue points. The incremental price for 1982 (hollow symbol) is excluded from the fit because 490 kilowatt-hours per year (kWh/yr) is well outside the estimated price–efficiency range for that year, so this point is derived from an extreme extrapolation.

**Table 2.** Results of fitting engineering-based price–efficiency estimates for refrigerators with a power-law model (3).

Year	$P_{\min}$	$P_{\text{UEC}}$	$\text{UEC}_0$	$\epsilon$	$R^2$
1982	1260	38.1	1350	2.32	0.995
1987	1270	20.7	925	6.47	0.991
1989	961	37.6	955	4.07	0.995
1995	796	67.9	700	2.65	0.993
2010	717	36.8	482	5.90	0.991

model in which price declines exponentially with time:

$$P_X = P_{X0} e^{-\alpha_X(t-t_0)}, \quad (4)$$

where  $X$  represents either the 1982-baseline-efficiency unit or



a unit with a UEC of  $490 \text{ kWh yr}^{-1}$  (see the SI for more detailed discussion of Moore’s-law type price trends). If the price of refrigerator efficiency mirrored the overall trend in refrigerator price, we might expect the incremental price of a fixed increase in efficiency to decrease at the same rate as the price of the least efficient refrigerator on the market: 2.5% per year. Assumptions similar to this have been used in recent appliance standards rulemakings that have incorporated experience curves [44]. Instead, the data presented here show that while the price of a fixed, low-efficiency refrigerator declines at that rate,  $\alpha_{\min} = 0.025$ , the incremental price of improving that efficiency by a fixed amount drops much more quickly:  $\alpha_{\text{UEC}} = 0.19$ , or a rate of price decline of roughly 19% per year between 1987 and 2010 (see figure 3(B))

In the SI, we present a similar analysis for four other appliances (side-by-side refrigerators, room air conditioners, central air conditioners, and clothes washers). In each case, we find a similar result: the typical decline in the price of efficiency is much faster than the decline in minimum appliance price. This rapid drop in the price of efficiency may be what has allowed the price of refrigerators and other appliances to continue to decline even as efficiency has improved. With the rapid decline of the incremental price, this price differential for an incremental efficiency improvement rapidly became small compared to the more slowly declining baseline price.

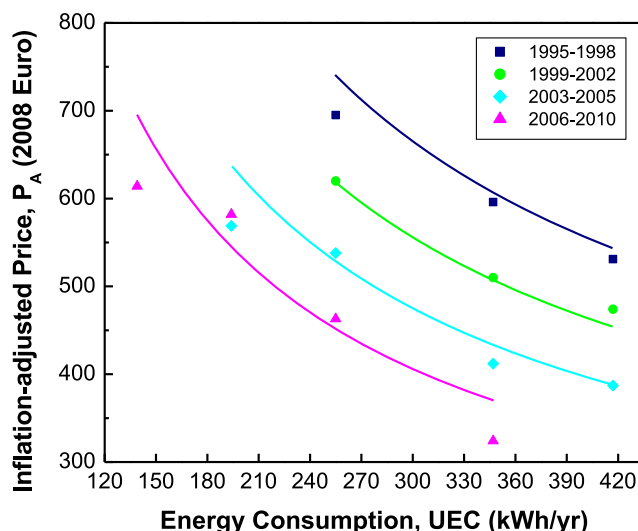
### 6. Price–efficiency trends for European Union refrigerators

While the results for US refrigerators give some indication that the price of efficiency may have rapidly decreased over time, engineering curves are estimates, not observed prices. Aggregated European refrigerator sales data from ten European countries (Austria, Belgium, Great Britain, Italy, the Netherlands, Germany, Spain, and France, Sweden and Portugal) enable the direct formulation of a statistical model that describes the observed efficiency-categorized price as a function of time.<sup>7</sup> Equivalent data are not available for the US because the US has not historically had labeling requirements with multiple EE categories.

As with the Netherlands data, we use sales-weighted averages of retail prices (not quality-adjusted) obtained from The GfK Group. We adjusted prices for both inflation and consumer purchasing power differences between countries [45] and converted all prices into 2008 Austrian purchasing power parity (PPP) Euros. We obtained comparative price indices for PPP adjustments between countries from table 1357 of the 2012 US Statistical Abstract [46].

We obtained refrigerator price data binned according to EE grade, which ranges from A++ to G for each country in the sample. The grades correspond to an energy efficiency index (EEI), which is defined as a unit’s energy consumption divided by the consumption of an average model (based on all

<sup>7</sup> Europe uses a substantially different refrigerator test procedure than does the US; energy use figures are not directly comparable.



**Figure 4.** Market-based price–efficiency estimates for European refrigerators illustrating the evolution over time. Points correspond to categorical averages over several years. Solid curves show the fit to these categorical averages using (5).

models on the market from 1990 to 1992) for units of the same adjusted volume. The European Commission adopted the grades in 1992 (92/75/EC). The grades were implemented into national ordinances between 1994 and 1998. The A+ and A++ grades were introduced in 2003 (2003/66/EC) and began being implemented in 2004. To scale the EEI to the energy use of a refrigerator, we set an EEI of 100% at  $463 \text{ kWh yr}^{-1}$ , the value the European Commission cited in its COLD II report [47]. Refrigerator capacity was assumed to be roughly constant during 1995–2009.

Similar to the Netherlands refrigerator analysis, European electricity prices are estimated using data from Eurostat [36] and UK DOE and Climate Change [37]. We use the same lifetime and discount rate assumptions as those for US refrigerators: 17.1 years and 5.0% per year, respectively.

We perform a simplified fit to the European data using (5) and assuming an exponential dependence of price on time (i.e. a form of Moore’s law: see SI for details):

$$P_{\text{UEC}}(\text{UEC}, t) = P_{\text{UEC}0} e^{-\alpha(t-t_0)} (\text{UEC}/\text{UEC}_0)^{-\epsilon}, \quad (5)$$

where  $P_{\text{UEC}0}$  is a reference price at a particular reference annual energy use  $\text{UEC}_0$  and reference time  $t_0$ . We utilized a simplified fitting function because the limited amount of data in each year did not support fitting the more complex form we used in the previous section.

Figure 4 shows the fit to the European market data, which describes the data reasonably well (see SI for additional details). Within a category corresponding to a particular EE grade, the average inflation-adjusted price declined by 4.5% per year between 1995 and 2009, while the average shipment-weighted inflation-adjusted price computed across all efficiency categories declined by approximately 1.3% per year. The market average estimated UEC simultaneously decreased by 4.2% per year. Because this analysis considers total price, not the incremental price of efficiency, it cannot be directly

compared to the results we obtained, in section 5. Nevertheless, as in the US, European refrigerator prices have declined even as the average efficiency on the market has increased.

### 7. Incorporating price trends in LCC optimization

To demonstrate how differential price trends by efficiency level can inform efficiency policy, we outline a conceptual framework for incorporating these trends in choosing an LCC-minimizing EE standard. We can combine (2) and (3) above to obtain an equation for LCC as a function of UEC. Minimizing this equation with respect to UEC then yields the following optimization condition (see the SI for a detailed derivation):

$$LCC_{\min} = P_A + \epsilon R_{UEC}. \tag{6}$$

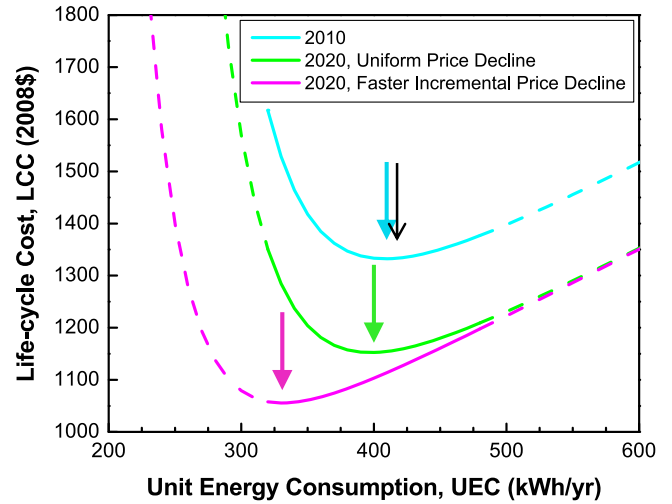
Inserting the Moore’s-Law model for the time evolution of price from (4) gives an equation for the time evolution of the minimum LCC:

$$LCC_{\min}(t) = P_A e^{-\alpha_{\min}(t-t_0)} + \epsilon R_{UEC0} \times \left( \frac{PVOC_L(UEC_0)}{\epsilon R_{UEC0}} \right)^{\frac{\epsilon}{1+\epsilon}} e^{-\alpha_{UEC}(t-t_0)/(1+\epsilon)}, \tag{7}$$

where  $PVOC_L(UEC_0)$  is the present value of the operating costs for an appliance with lifetime  $L$  whose UEC is equal to  $UEC_0$ .

Figure 5 illustrates using these equations to forecast the UEC that minimizes refrigerator LCC in 2020, based on the 2010 price–efficiency relation shown in figure 3(A). If the price of all refrigerators is predicted to decline by 2.5% per year regardless of efficiency level, the LCC-minimizing UEC is expected to decline from 410 kWh yr<sup>-1</sup> in 2010 to 400 kWh yr<sup>-1</sup> in 2020. This is the approach to price trends that is currently used in DOE EE standards analysis, and which was first utilized in support of the refrigerator standard issued in 2011 [44, 48]. If, instead, the incremental price of efficiency is forecast to decline at 19% per year (while  $P_{\min}$  continues to decline at 2.5% per year), the LCC minimum point is expected to decrease an additional 17.5% to 330 kWh yr<sup>-1</sup>, yielding an additional LCC reduction of \$97 for each of the estimated 13 million refrigerators sold in the US in 2020 [48]. If all the refrigerators purchased in 2020 saved the additional 70 kWh yr<sup>-1</sup> enabled by the faster incremental price decline, they would save a cumulative 15 TWh of electricity over their 17-year lifetime, which corresponds to approximately 9 million metric tons/yr of avoided CO<sub>2</sub> emissions with present-day electricity generation.

Determining price trends at the required level of granularity for an incremental-price forecast is challenging, and it may often be impossible to produce such forecasts with sufficient certainty for use in a regulatory analysis. In this case, given the potentially rapid price evolution of efficient technologies, regular regulatory updates are especially important



**Figure 5.** Dependence of LCC on baseline and incremental price declines. The blue curve shows the dependence of refrigerator LCC on UEC in 2010 according to the model in figure 3(A) (the LCC rises at high UEC because increased energy costs outweigh decreased price). The solid portion of the line indicates the range of efficiencies considered in the refrigerator rule published in 2011. The green curve shows how the LCC may change in 2020 if both the baseline and incremental price of efficiency decrease at 2.5% per year. The magenta curve illustrates how the LCC in 2020 may change more rapidly if the incremental price decreases at 19% per year instead. The arrows with corresponding color indicate the LCC minima. The black arrow indicates the minimum efficiency performance standard that was issued in 2011 and went into effect in 2014.

to maintaining EE policies that are close to the social optimum.

### 8. Conclusion

By examining the history of appliance standards for refrigerators, clothes washers, room air conditioners, and central air conditioners in the US, and refrigerators in the Netherlands, we observe an accelerated decline in LCC post-standards in all cases studied and an accelerated decline in price for clothes washers, room air conditioners, and central air conditioners in the US, and refrigerators in the Netherlands. The more pronounced acceleration in the rate of decline in LCC compared to price is unsurprising because EE standards are specifically designed to reduce energy consumption, and therefore operating costs. We also find that the incremental price of efficiency decreased faster than the baseline price for top-mount and side mount refrigerators, clothes washers, room air conditioners, and central air conditioners in the US, which may help explain the sustained long-term price decline under standards, although more research is still needed to understand what has driven these accelerated price declines. Additionally, we observe price declines in the retail prices of European refrigerators during an EE policy era.

Since 1978, the US DOE has analyzed energy-efficiency standards for a growing number of residential appliances and devices using a standard-setting process that is governed by a number of procedural and technical requirements. The

regulatory analysis of each standard includes a ‘bottom-up’ engineering estimate for the incremental cost of achieving higher efficiency. Prior to 2011, declines in cost described by learning curve trends were not included in this analysis. Since 2011, learning-curve trends have been used in the determination of US appliance efficiency standards. The regulatory analysis currently uses only the learning trends of the base price and assumes no additional decline in the incremental price of efficiency. The present analysis suggests that this remains a conservative analytical approach for the appliances considered here.

Our analysis indicates that the rate of price decline for the incremental price of efficiency in some cases may be as much as an order of magnitude faster than for the baseline price. If this observation is correct, better modeling of the potentially much faster price decline for efficient technologies may produce more accurate forecasts of cost-effective energy savings. Future research could help determine how to model dynamic market reactions to regulation and the potentially complex time dependence of market distributions for regulated products. Further research into the explanation for these patterns could also help policy makers determine how and when it may be appropriate to include these new modeling approaches in the regulatory process.

Possible explanations for the observed accelerated decline in price and faster rate of decline for the incremental price of efficiency may be indicated by recent work undertaken by Spurlock [12] and Van Buskirk [10]. Spurlock modeled the downward trend in clothes washer price after federal clothes washer standards in 2004 and 2007 using a second-degree price discrimination model and found a particularly pronounced downward trend at higher efficiencies. Van Buskirk explored the dynamics of the European refrigerator market using a learning-by-doing model and found a faster learning rate for higher efficiency products based on their relatively low market adoption and more rapid increase in cumulative production. Additionally, some of the observations of the accelerated price decline under standards may also be explained as a spillover effect [49] of improved efficiency technology. That is, learning-curve-driven productivity improvements in the manufacture of high-efficiency products could spillover and potentially yield productivity improvements for baseline products.

Substantial research will likely be required to determine whether new modeling techniques can reliably produce forecasts consistent with empirical observations. But if such new models can be developed, they may improve forecasts of cost-effective energy savings. This would likely aid in the development of more optimal energy-efficiency policies that could provide additional economic benefits for consumers.

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